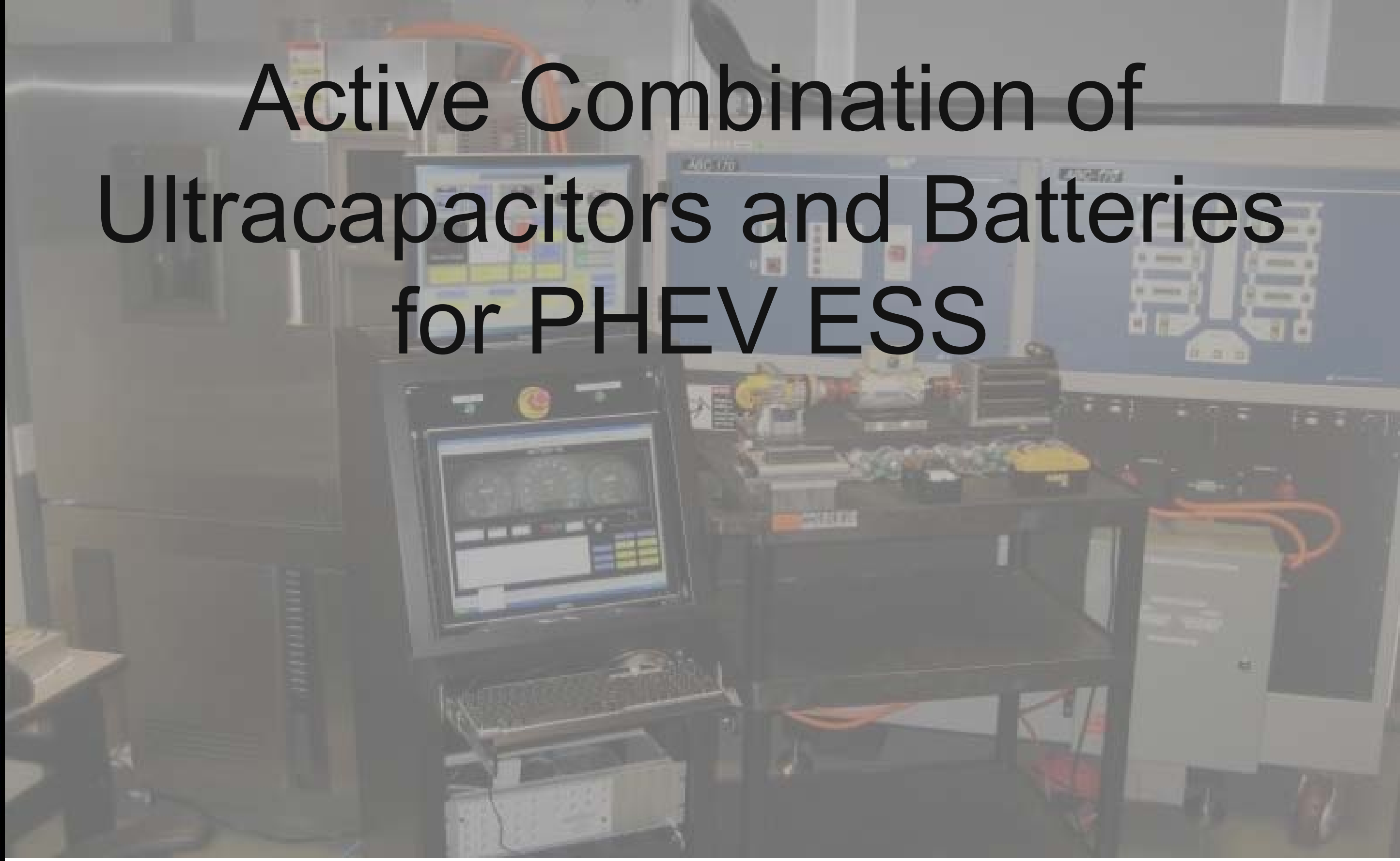
Active Combination of Ultracapacitors and Batteries for PHEV ESS



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Sponsored by Lee Slezak

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U.S. Department of Energy

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*Dan Bocci- Ultracap simulations/controls software
Neeraj Shidore- Battery HIL collaboration

Actively Coupled Ultracapacitor-Battery System Project Overview

Timeline

- Started in mid 2007
- FY2008 completed hardware proof of concept testing
- FY2009 Controls integration work and initiate long term effects study
- 80% complete

Budget

- FY2008- $200k received
- FY2009- $800k received
- Many other ANL tasks support this effort

Barriers

- Cost of Li-Ion battery for PHEVs
- Durability on 10 year battery warranty
- Reduced battery power capability at low temperatures
- Advanced control software to adequately regulate ultracapacitor state-of-charge for actively coupled system needed
- Cost/size of power electronics to actively couple components are too high

Partners

- Maxwell Technologies Inc.
- Gold Peak Battery-USA
- ANL Chemical Sciences Engineering Division, battery test facility (ESTT)

<u>Objective:</u> Investigate Benefits of Active Combination of Ultracapacitors and Advanced Chemistry Batteries

- Create a <u>high power</u> and <u>high energy</u> electrical storage system that has equal or better system efficiency and net cost/density as current conventional batteries.

- Demonstrate, via long term testing of sub-pack assemblies, that reducing the stress on lithium polymer batteries via actively coupled ultracapacitors can achieve the benefits indicated by simulation results.

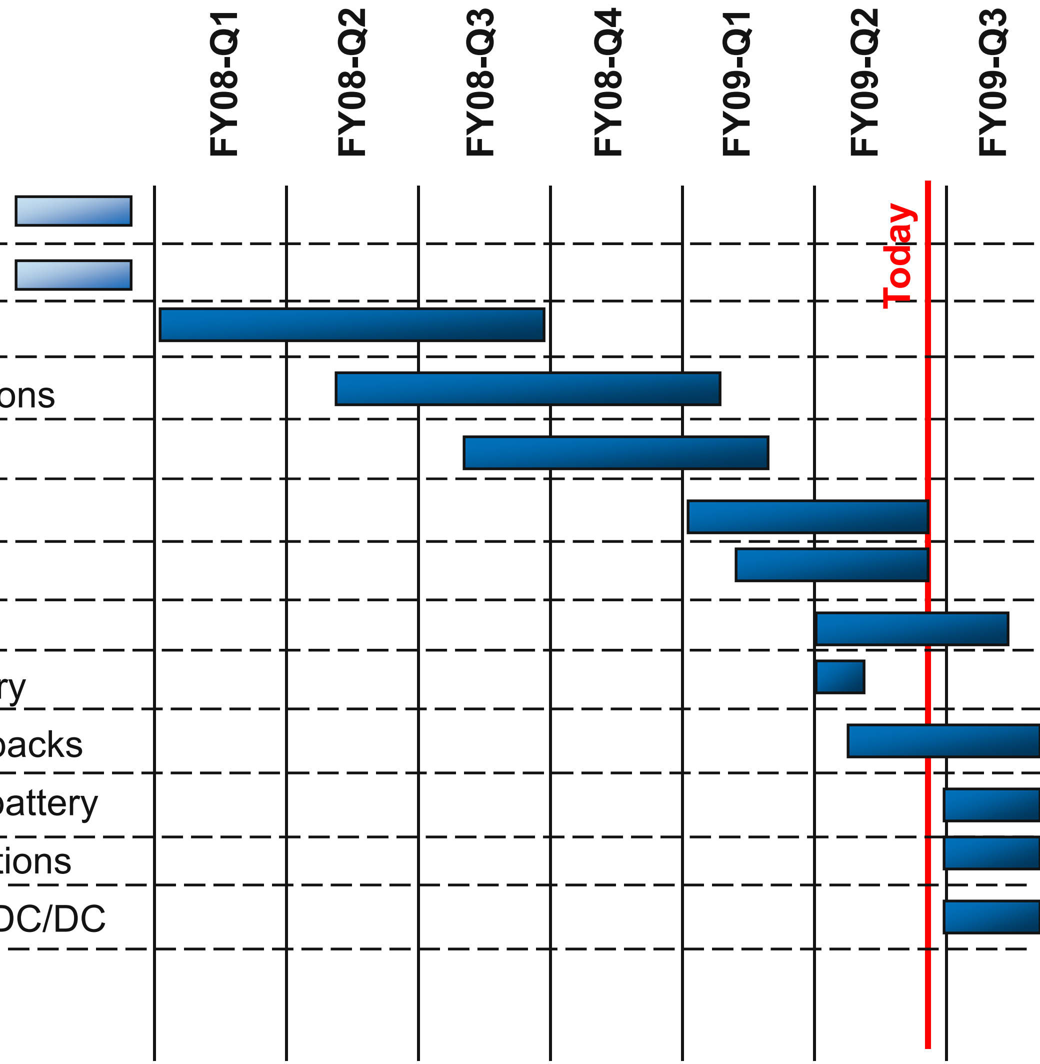
- Develop new SOC control strategies for ultracapacitor bank power blending.

- Identify component costs for net energy storage system hardware and opportunities to explore technologies that will reduce that cost (such as higher frequency DC-DC converters)

- Demonstrate that limiting peak power delivered by the li-ion battery, especially in cold weather operation where the li-ion battery may be damaged at high loads, will remove the need to oversize the energy storage system, thus saving battery costs.

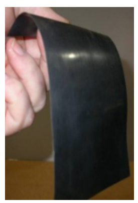
Milestones for FY08 an FY09

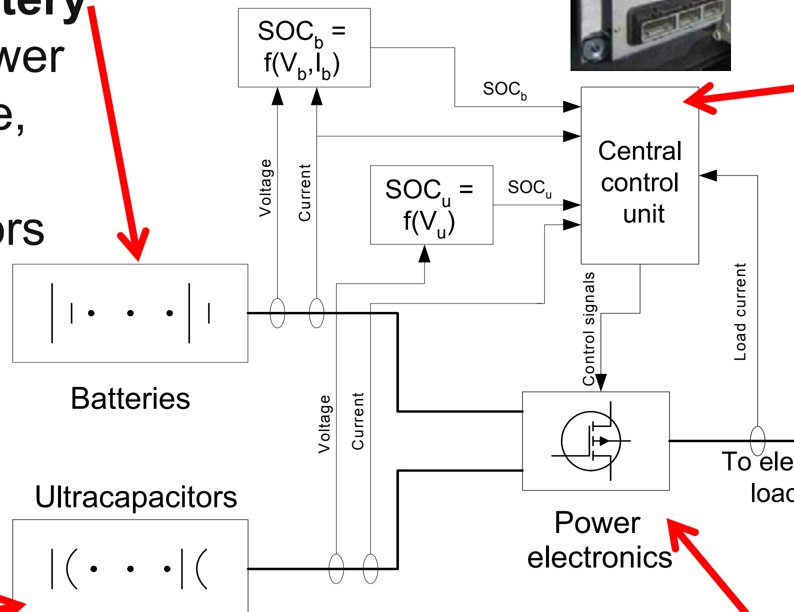
- 2007- Feasibility study on ESS/ultracaps
- 2007- Collaborative agreement w/Maxwell
- Component level modeling of ESS types
- Specify experiment components via simulations
- Commission cutting edge DC-DC converter
- Develop SOC regulation controls software
- Simulate EES behavior with SOC controls
- HIL Validation testing with 36V subsystem
- Collaborative agreement w/Gold Peak Battery
- ~24 month cycling on 3 Li-ion (36v) UC/subpacks
- Investigate methods for high energy dense battery
- Explore ultracapacitor cost/packaging reductions
- Identify power electronics advancement for DC/DC



Technical Approach: Four Key Elements in Actively Coupled Ultracapacitor and Battery for PHEVs

Energy Optimized Battery
Trade off energy for power with very thick electrode, that complements high energy density capacitors





SOC Controller
develop algorithm tuned for max battery life, aggressively utilizing all of the capacitor energy

Reduced Cost EDLCs
Capacitor construction technology that reduces labor cost (machine assembled with fewer parts)

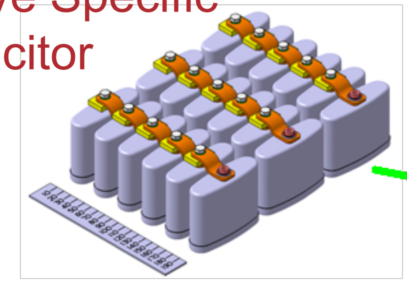
DC/DC Converter
Aggressive cost/mass reduction- \$15-\$25/kW, high frequency (200kHz), SiC devices, powdered inductors magnetics

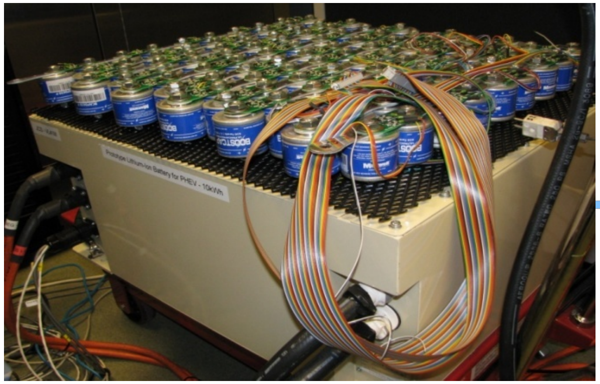
Tradeoff conventional battery volume/cost for net increased performance including batteries, electronics, caps

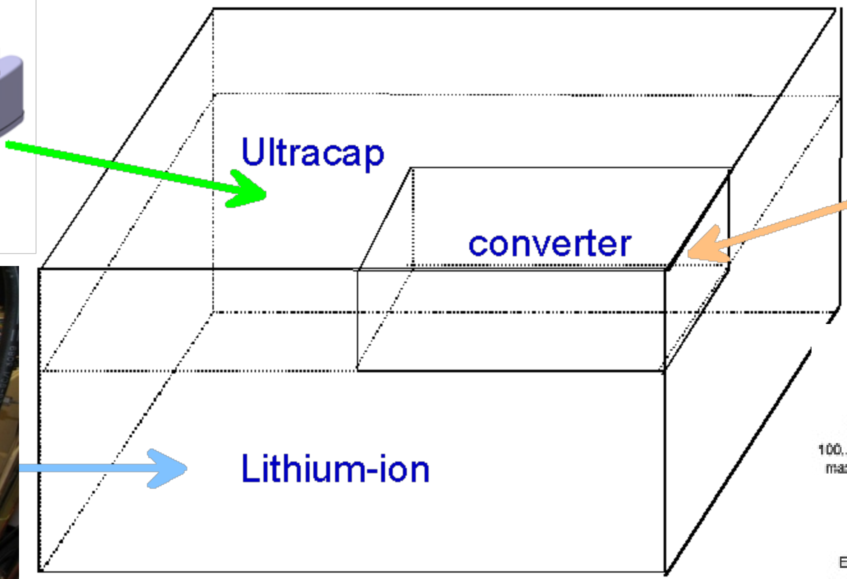
System design targets optimized energy lithium-ion as budget to pay for added cost of ultracapacitors and lithium-ion.

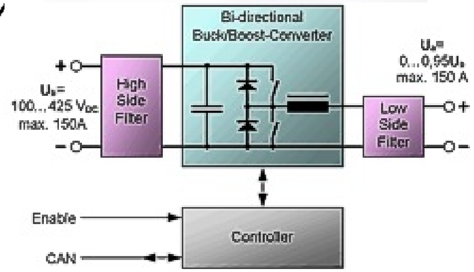
- PHEV to EV pack using Thi$_{c}$k*flex* electrode saves 8% to 11% volume
- Thick electrode on lithium-ion can save up to $285/kWh
- Cost & volume budget for dc-dc converter + ultracapacitors

Automotive Specific Ultracapacitor



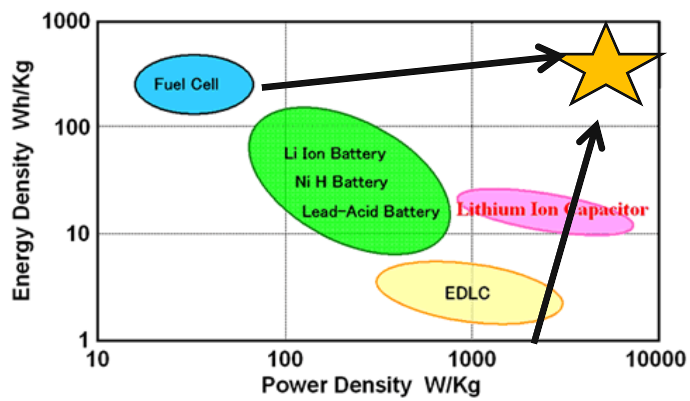


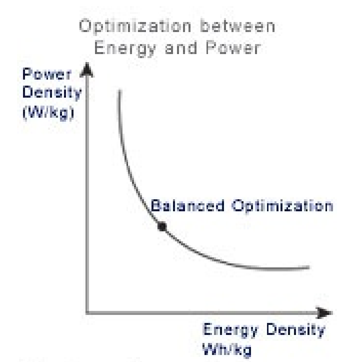




Benefits of Ultracapacitor Bank actively coupled via power electronics in PHEV/EV energy storage system

1) Allows optimized energy density battery (150 to 400Whr/kg?) by reducing peak loads and minimizing internal battery heating (move I^2*R losses out)
2) Guaranteed end-of-life ESS power capability (i.e. no capacitor power fade), as well as reduced need to oversize battery for end-of-life performance.
3) Full power delivery (from UC/Electronics) in cold weather, allowing more engine-off operation for PHEVs in those conditions.
4) Full power acceptance at high SOC (i.e. full regen braking/recovery when battery is above 80% SOC)
5) Trade off reduced battery size for separate subsystems (i.e. easier to package since capacitors/electronics don't share battery cooling system)

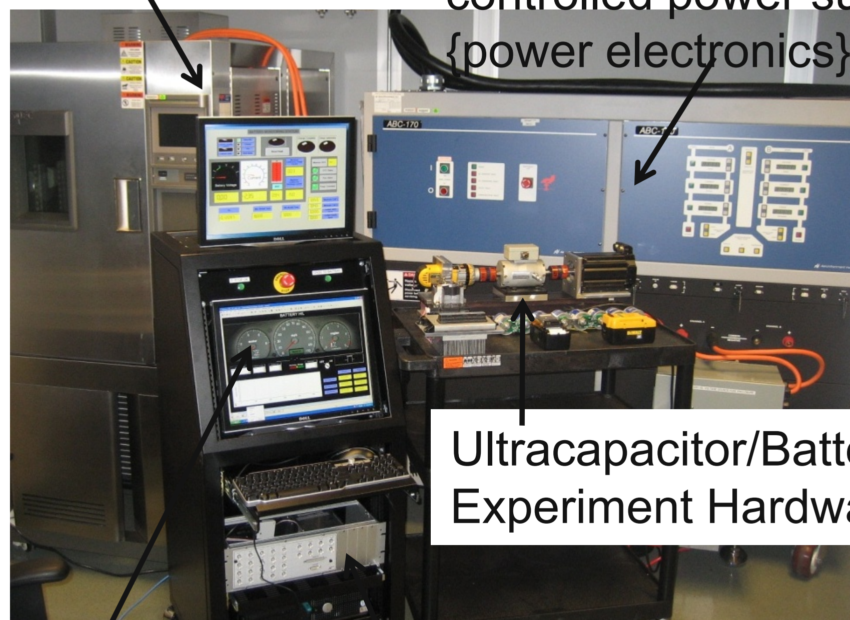




Technical Accomplishments

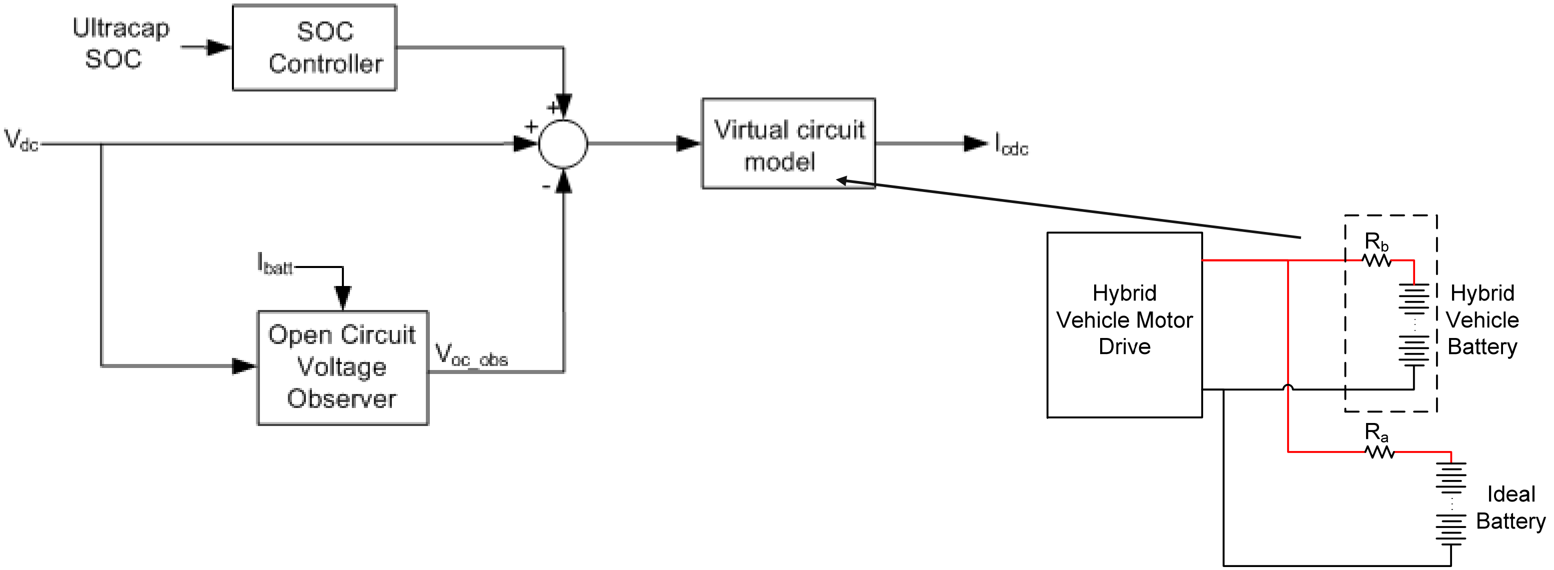
- Feasibility studies and preliminary component/circuit level simulation completed.
- Scaled down capacitor bank fabricated for initial HIL low risk experiments
- Combined scaled capacitor bank with scaled down li-ion battery Dewalt 36v/2.3Ahr (cordless tool pack) based on A123 cells. Ran 100A peak power profile. (full current, scaled voltage)

36v/2.3Ahr Li-ion battery
36v 650F Ultracap bank



Four Iterated Approaches to SOC Controller

1. Active Resistance
   In this approach the ultracapacitor behaves as a second battery with significantly lower internal resistance, actively varied as a function of the power electronics.

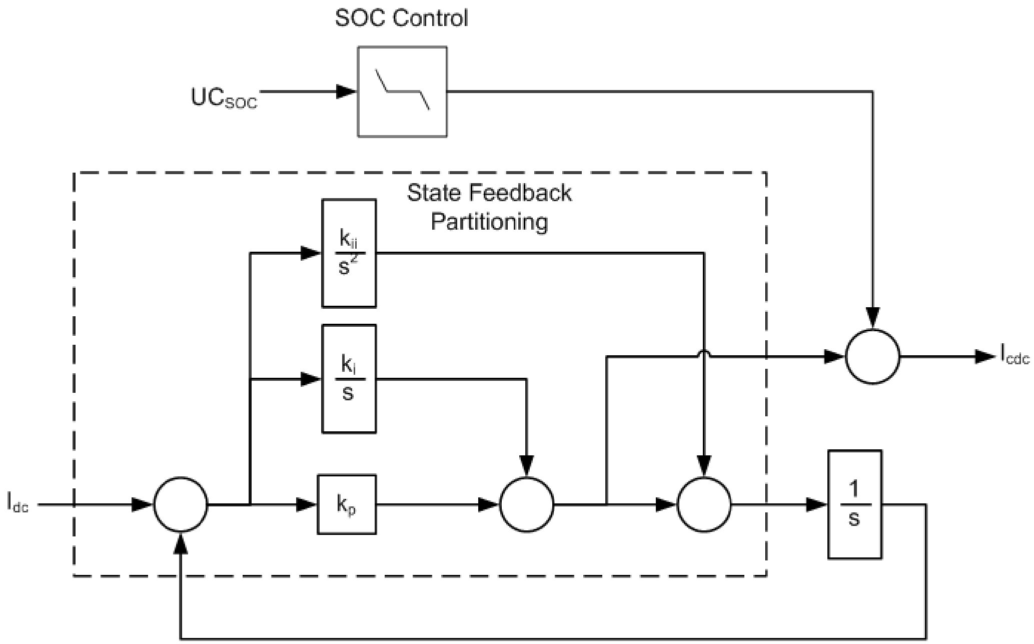


Drawbacks for this method are that it is not as robust as other control methods, somewhat complex to properly tune, and that an open circuit voltage observer requires accurate battery parameter information.

Four Iterated Approaches to SOC Controller

2) State Feedback Partitioning (SFbP) w/ static SOC set point

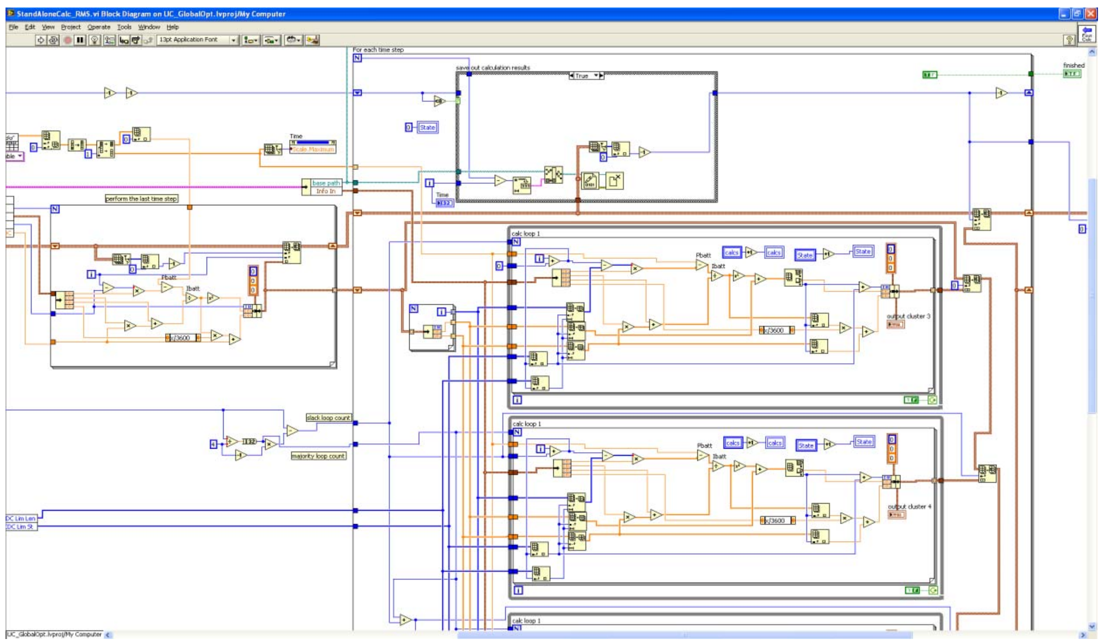
In this approach the battery/ultracap current proportions are frequency based where the fast transient components are handled by the ultracapacitor bank and the slower demand by the battery. The SOC controller attempts to maintain 50% SOC to balance power delivery and acceptance capacity. This method is easier to tune than the first method.



Four Iterated Approaches to SOC Controller

3) <u>Global Optimization</u>

- Uses the ideal power model of battery and ultracapacitor, but requires full knowledge of the future power demands.
- Provides benchmark for the best possible results. The Labview implementation is shown below as a multi-threaded approach leading to fast execution times. The cost function (in global optimization lingo) is assigned to reduce battery RMS current, which also leads to reduced ohmic losses. It is based on a simple power based model.



Four Iterated Approaches to SOC Controller

4) <u>State based Feedback Partitioning (SFbP) with dynamic SOC set point</u>

-Similar to the control block diagram for strategy #2.

-Strategy splits the Battery/Ultracapacitor current based on frequency (ultracap for fast current demands, battery for slower demand).

-The SOC controller uses vehicle speed to determine correct ultracapacitor SOC regulation (as a dynamic set point).

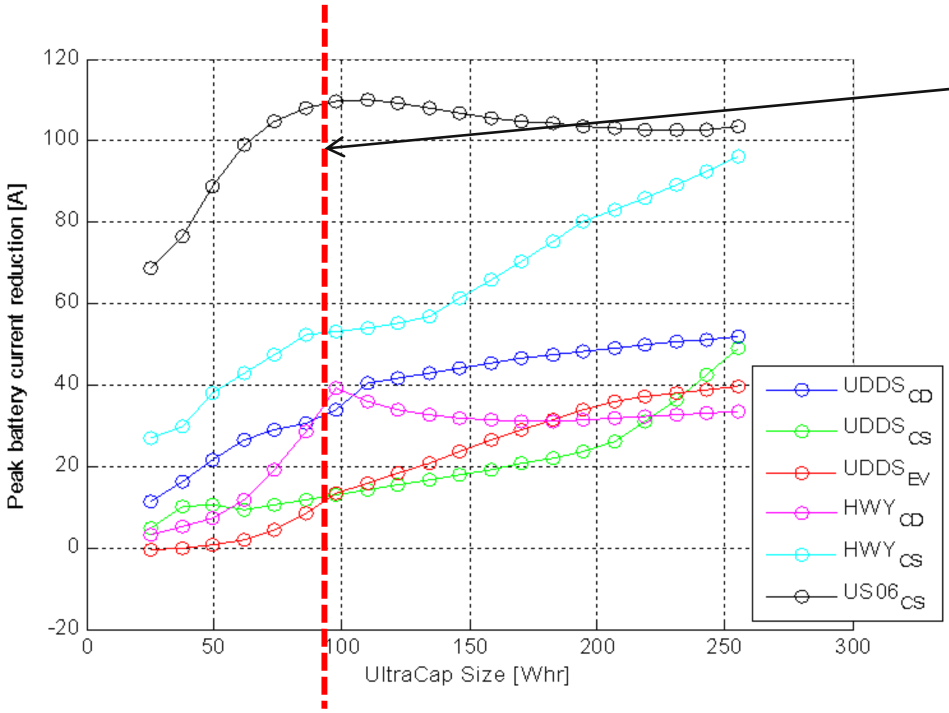
-Vehicle speed input is used to ‘predict’ the next direction for the current command.

-For example is the vehicle speed is 60mph, it is likely the next current demand will be for regenerative braking and the capacitor SOC is diminished anticipating incoming charge.

Results

Simulation Study of Capacitor Sizing

The graph below shows that as the capacitor bank size (stored energy) is increased (with the State Feedback Partitioned controller frequency at 0.01Hz and SOC gain at 200A/%) there is a point of inflection around the **100 Whr mark** for the various drive cycles in a PHEV Saturn Vue sized vehicle. This is the point where the system controller can handle all the current requests

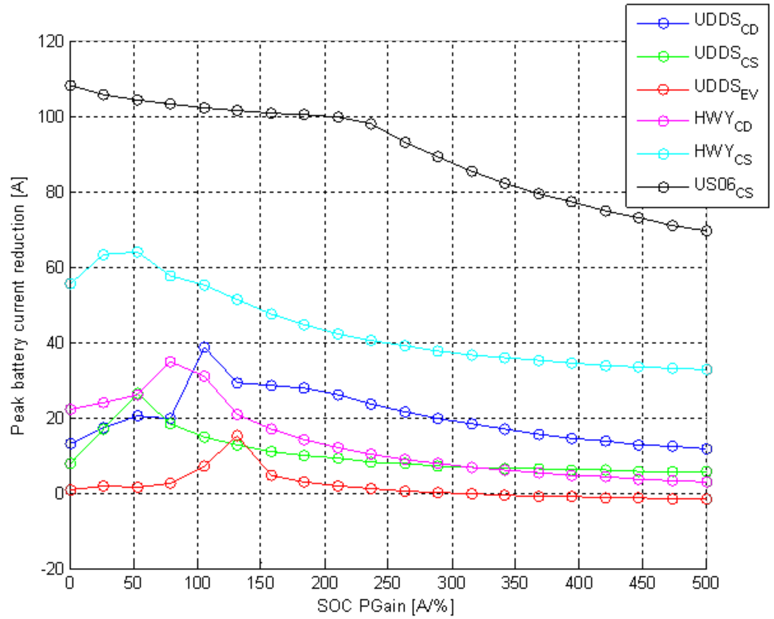


Shows that 75-100Whr Capacitor bank is appropriate

Results

<u>SOC Gain Tuning:</u> The simulation results plot below shows the variation of SOC gain from 0 to 500A/% for the various drive traces and a 64Whr capacitor bank, SFbP gain of 0.01Hz.

It also shows that if the gain is set too high the SOC window goes unused for these drive traces and is effectively reduced. It also shows that SOC gain must be dynamically adjusted (not fixed) to yield consistent results.

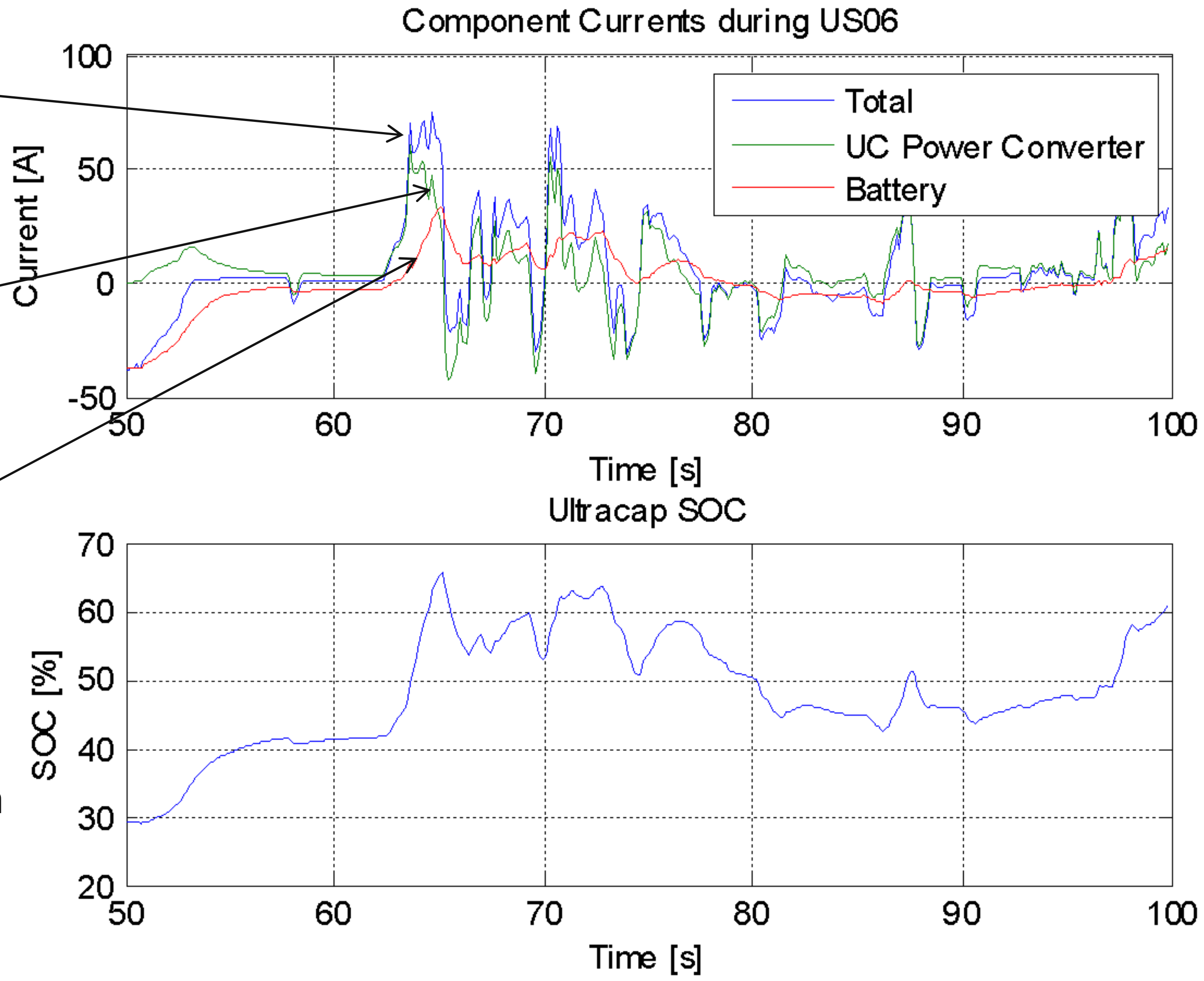


Currents vs Time, Net Change in Battery Current

Blue line is road load (battery current w/o ultracaps)

Green line is U-cap current (dynamic)

Red line is new battery current- more averaged.



SOC is maintained over this ‘real world’ Prius current trace, on US06 segment

Investigating Long Term Effects of Active Combination of Ultracapacitors w/Energy Optimized-LiMnO2 Polymer Batteries

Polymer Cells, BMS

Sub Pack of 10 cells (10*3.8v/30Ahr, 9.30kg)
4.75”L x 1.25”W x 5.5”H each, 12.5”W total

Long Term Testing: 3 x 10 module packs

1) Full vehicle current (3C peaks, <100 amps).

2) Direct parallel capacitor bank of 650F cells, 38v nominal. The combination will see full vehicle current.

3) Active combination of ultracapacitors w/ sub-pack of 10 modules. Battery sees reduced magnitude and di/dt currents (~1C rates) battery will see ~1C peak currents.

Cells are rated at rated at 1000 cycles at 25 degC, 70% DOD. Looking for statistically significant differences in battery life between the 3 subpacks test (3000 cycles?).

Future Work:

- Active combination of ultracapacitors with batteries for PHEV applications is a multi-year program. This work will leverage interest from OEM's, DOE EE-Tech Team & ES-Tech Team.

- Continue tuning controller software to balance SOC window with aggressiveness of peak power reduction from the battery side of the energy storage system using insights gained on Battery HIL test stand and ABC170 as DC/DC converter.

- Investigate limitations of battery only ESS at high state of charge, low operating temperatures, as well as estimated reduction in power capability at end of life. Run same battery at these conditions with and without actively coupled ultracapacitor system.

- Conduct studies and experiments for power electronics components size and cost reduction as well as lower-cost controller hardware.

Future Work:

- Implement lower power density, higher energy density battery on Battery HIL stand with actively coupled ultracapacitor to illustrate ESS optimized for energy in battery, for power with ultracapacitor via active coupling using power electronics.

- Complete implementation of control software in MotoTron ECM and Brusa BDC412 DC/DC converter. Run system with 300v; 72Whr ultracapacitor bank in PHEV and HEV. Investigate the impact on cold weather operation, and reduction of system losses for a wider usable battery SOC window (Prius).

- Work with OEM and Tier I suppliers to identify production cost/size of a DC/DC converter that meets requirements for actively coupled ultracapacitor system and energy optimized battery for Chevy Volt sized PHEV.

11.5kWhr 380v/30Ahr (93kg) Gold Peak PHEV Battery Pack

HIL w/Kokam Batteries

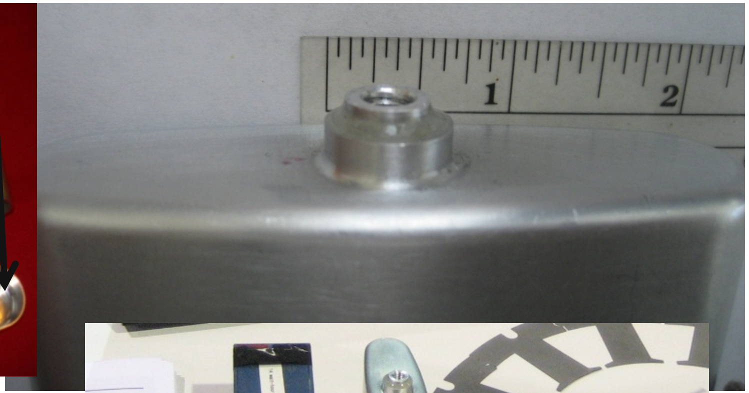
Maxwell 150-um thick flexible films (Thi$_{c}$k*flex* electrode). Film thickness of 250-1000 microns demonstrated

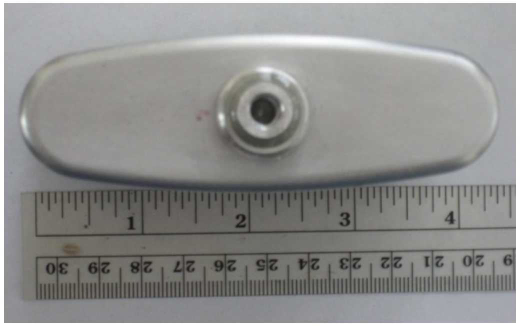
OEM Involvement

- Maxwell Technologies is investing resources in new capacitor form factor, as well as bipolar li-capacitor technology. (building 18 cell evaluation pack)
- Gold Peak USA is collaborating by supplying prototype LiMnO2 polymer batteries.
- Magna Corp will use ANL ultracap/power converter on prototype OEM EV for 2012 California ZEV Mandate (Mar-June 2009 tests)
- Continental Automotive, as well as US Hybrids are working on reduced cost, highly aggressive DC/DC converter designs.
- GM has verbally committed to use this technology on Chevy Volt ESS, and lab evaluation.
- Proctor and Gamble interested in developing processed to fabricate lower cost, higher energy density batteries using paper/web handling methods.

New Form Factor Ultracapacitor

- Deep drawn can, square-ish shape easier to stack; 93mm W, 32mm D, 90mm H(w/fastener) (3.66” x 1.26” x 3.54”H), 170g.
- Coaxial terminals (both +/- on one bolt)
- Machine assembled; 3 sonic welds-
  1) foil to can, (+) terminal
  2) foil to center pole (-) terminal
  3) (electrolyte fill) sonic weld bottom cover





Current cylindrical form factor for comparison in size

Summary: Active Combination of Ultracapacitors and batteries for PHEVs can allow an optimal tradeoff between high power density ultracapacitors and energy optimized batteries.

1) Allows optimized energy density battery (150 to 400Whr/kg?) by reducing peak loads and minimizing internal battery heating (move I^2*R losses out)

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Support of Other DOE Programs

Energy Storage Tech Team

-*Battery performance/reliability improvement study*
-*Explore other batteries best matched with U-Caps*

EE Tech Team

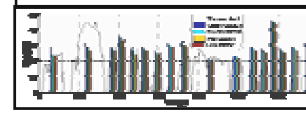
-*Power electronics component costs*
-*Control bandwidth algorithms for SOC/tracking*
-*Cost of embedded controls/processors*

PHEV Development Platform

Ultracap Studies

-*Cold weather/battery limitations*
-*Cost reduction challenges*
-*Charge-efficiency assumptions/studies*

Battery HIL



PSAT at ANL

- *Vehicle level simulations and component validation/sizing*